Forest Ecology and Management 310 (2013) 857–864

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Effects of the pruning intensity and tree size on multi-stemmed *Prosopis flexuosa* trees in the Central Monte, Argentina

Juan A. Alvarez [a,b,*], Pablo E. Villagra [a,b], Ricardo Villalba [a], Guillermo Debandi [c]

[a] *Departamento de Dendrocronología e Historia Ambiental, Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales, IANIGLA, CCT Mendoza, CONICET, (CC 330, 5500) Mendoza, Argentina*

[b] *Facultad de Ciencias Agrarias, Universidad Nacional de Cuyo, (M5528AHB) Chacras de Coria, Mendoza, Argentina*

[c] *Asociación para la Conservación de la Diversidad Biológica Argentina, BIOTA, Bosques Telteca 2237 (5509), Luján de Cuyo, Mendoza, Argentina*

ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form 16 September 2013
Accepted 18 September 2013
Available online 13 October 2013

Keywords:
Pruning
Prosopis
Arid woodlands
Multi-stemmed trees
Silviculture

ABSTRACT

Forestry use in *Prosopis flexuosa* woodlands in the Central Monte is limited by low wood productivity and by most of the trees being multi-stemmed. Desert inhabitants have turned pruning into a common practice to get some forest products, increase wood production and improve tree shape. In this study we tested pruning practices used by locals on trees of different diameter classes and different pruning intensities in the aeolian plains of the Central Monte Desert. Two trials were conducted: (a) we tested the effects of pruning on three types of trees: adult multi-stemmed trees (7.5–15 cm basal diameter; $n = 12$ for pruned trees and 10 for control), young trees (3–7.5 cm basal diameter; $n = 20$ for pruned trees and 18 for control), and saplings (<3 cm basal diameter; $n = 15$ for pruned trees and 18 for control); (b) we compared the effects of different pruning intensities: heavy pruning (50% of crown removed and $n = 10$), intermediate pruning (25% of crown removed; $n = 10$), and unpruned individuals ($n = 10$). Basal diameters of all stems, total tree height, largest and smallest crown diameters were measured yearly. We estimated the equivalent basal diameter (EBD) and crown volume. Linear mixed models (LMM), in continuous variables, and general linear mixed models (GLMM), in discrete variables, were used for evaluating the effects of the treatments on the different variables. The response observed in pruned trees was an increased length of branches, which in both trials translated into increased crown diameter and volume. No initial response was recorded in basal diameter growth of the remaining stem. In adult trees, an increase in basal diameter was detected five years after pruning. A greater response of crown growth was found in individuals subjected to heavy pruning vs. individuals under intermediate pruning. Results suggested that pruning could improve the shape of *Prosopis* in the short run, and increase stem diameter growth in the long run, as observed for other tree species of *Prosopis* that received pruning throughout the world. This suggests that this practice could be potentially used to obtain poles and firewood without a decrease in wood productivity but with an increase in branch growth, and, in consequence, it could be included in silvicultural management of woodlands dominated by multi-stemmed trees and in models of sustainable management at local scale.

1. Introduction

The man of the desert has, since ancient times, resorted to pruning as a management tool to get diverse profits from dryland trees. The genus *Prosopis* consists of more than 40 species of trees and shrubs widely distributed across arid and semiarid regions of the Americas, east of Asia and north of Africa (D'Antoni and Solbrig, 1977). Numerous adaptations (response to herbivory, tolerance to drought and saline soils) have allowed these legumes to dominate the woody vegetation in arid regions (Fagg and Stewart, 1994). Since antiquity, there is a close relationship between trees of this genus and different human groups (D'Antoni and Solbrig, 1977; Roig, 1993). The great variety of products and ecosystem services that these trees provide determines that they be considered multiple-use species (F.A.O., 1994; Cony, 1995; Tewari and Harsh, 1998). In different regions, the wood's good quality, color and mechanical features have given rise to markets for forest products derived from extraction of plant parts (pruning) and, in some cases, from thinning or selective logging of *Prosopis* trees (Patch and Felker, 1997a, 1997b; Felker and Guevara, 2003; Villagra et al., 2005).

* Corresponding author at: Departamento de Dendrocronología e Historia Ambiental, Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales, IANIGLA, CCT Mendoza, CONICET, (CC 330, 5500) Mendoza, Argentina. Tel.: +54 261 5244209; fax: +54 261 5244200.

E-mail address: jalvarez@mendoza-conicet.gov.ar (J.A. Alvarez).

0378-1127/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2013.09.033

Pruning, as an improver of wood quality, is amongst the most commonly used silvicultural practices in the management of *Prosopis* woodlands (Patch et al., 1998). Removal of secondary stems and small branches seeks to improve growth habit and increase the quantity and quality of wood produced (Patch and Felker, 1997b; Elfadl and Luukkanen, 2003). In Arizona, USA, such pruning combined with inhibition of resprouting buds has been applied to young trees of *Prosopis glandulosa.* Pruning is also associated with significantly increased photosynthetic rate in *P. juliflora* (Elfadl and Luukkanen, 2003), a response which can also be used to optimize wood and fruit production of *Prosopis* species (Diaz Celis, 1995; Pasiecznik et al., 2001). The effect of pruning and thinning has generally been studied in plantations but not in native woodland (Elfadl, 1997; Patch and Felker, 1997a, 1997b).

In defining management practices, the shape of the tree determines the quality of forest products to be obtained. According to Meyer et al. (1971), those *Prosopis* species belonging to the Algarobia section show a high tendency to have apical dominance and, consequently, good crown development. *Prosopis flexuosa* is a tree with deciduous leaves that occurs in arid regions of Argentina and the central north of Chile, occupying vast sectors of the South American arid diagonal (Alvarez and Villagra, 2009). Open woodlands of this species grow on sandy plains with water available from water tables lying close to the ground surface (between 6 and 12 m) where it behaves as a phreatophyte (Rundel et al., 2007; Aranibar et al., 2011). In north-western Argentina, single-stemmed trees represent 83% of the *P. flexuosa* population (Mooney et al., 1977; Cony et al., 2004); therefore, these woodlands show the possibility of controlled management with extraction of forest products of high economic value (wood for furniture or floorboards). In contrast, in Southern *Prosopis* woodlands in the Central Monte desert, more than half of the trees are multi-stemmed or have their main stem highly branched with secondary branches showing nearly horizontal growth (semi-erect), or with pendulous lateral branches that reach the ground (decumbent) (Alvarez et al., 2006; Villagra et al., 2005). These characteristics and the low productivity (140–170 kg ha^{-1} $year^{-1}$) restrict forestry use of the woodlands of Mendoza. Moreover, the growth rate of multi-stemmed individuals decreases rapidly since 60 years of age whereas single-stemmed trees do not show such decrease, suggesting the existence of competition between stems in adult individuals (Alvarez et al., 2011a). Thus pruning could eliminate such competition, preventing the observed reduction in growth rate. However, the consequences of pruning would depend on the balance between the positive and negative effects produced by this treatment. Among the positive effects are decreased competition between stems and reallocation of assimilates or photosynthetic compensatory effects (increase in the photosynthetic capacity of remaining foliage) (Helms, 1965; Heinchel and Turner, 1983). Among the negative ones, in addition to the obvious reduction of the photosynthetic area of the plant, are root mortality and loss of reserves (Allen, 1986; Peter and Lehmann, 2000; Bayala et al., 2004).

We hypothesize that pruning eliminates competition between stems, so we expect a higher annual growth of the remaining stem in pruned trees than in control trees. Furthermore, as this competition among stems increases with the age of the tree (Alvarez et al., 2011a), we expect a higher response to pruning in adult than young and sapling *Prosopis* trees. Finally, we hypothesize that growth response to pruning will be lower in heavily pruned trees than in trees subjected to intermediate pruning due to the higher proportion of crown biomass loss. Our objectives were: (a) to analyze whether pruning increases diameter or crown growth in *P. flexuosa* individuals of different diameter classes from the Central Monte desert and (b) to investigate the effects of pruning intensity on both stem diameter and crown growth in young *P. flexuosa* trees.

2. Materials and methods

2.1. Study area

The study area is located in the central plains of north-eastern Mendoza, Argentina (32–33 S, 67–68 W; 500–550 m elevation). This area, including Telteca Reserve (38.507 ha) and surrounding lands, is representative of the central zone of the Monte Biogeographic Province (González Loyarte et al., 1990). It is located in a sedimentary basin between two geological structures with positive relief, the Cordillera de Uspallata in the west and the San Luis Sierras to the east. The aeolian reworking of Holocene sediments originated a system of transverse sand dunes up to 20 m height separated by 100–200 m wide troughs (González Loyarte et al., 1990). The climate is arid with total annual precipitation around 156 mm (1972–2007 average), and large daily and annual temperature ranges. Mean temperature is 18.5 °C, with absolute maximum and minimum being respectively 48 °C and −10 °C (Estrella et al., 1979).

This study was conducted in open woodland of *P. flexuosa* (25% of tree cover), accompanied by *Trichomaria usillo* and *Suaeda divaricata* as main shrubs (tree density: 155 trees per ha^{-1}, between 103 and 186 trees). Diameter structure indicates low number of trees of intermediate classes, between 20 and 35 cm in equivalent basal diameter (the diameter corresponding to a one-stemmed individual with an equivalent basal area), and absence of individuals with large diameter stems. This woodland has the highest concentration of individuals with diameter between 2.5 and 17.5 cm (Alvarez et al., 2006). In all, 61% of adult trees have more than one stem (trees were considered adults with diameter >7.5 cm).

2.2. Experimental design

2.2.1. Trial I. Pruning in Prosopis individuals of different diameter classes

Three types of multi-stemmed *P. flexuosa* trees were selected according to basal diameter of the main stem (SBD). Individuals with SDB between 7.5 and 15 cm were considered adults, those with SBD between 3 and 7.5 cm were considered young, and saplings were those individuals with SBD < 3 cm. For each diameter class, we selected individuals with similar growth habit on similar site quality: 24 adult trees, 40 young trees and 36 saplings. Half the trees in each class were pruned and the other half was left unpruned. As some mortality was observed after the first year of the assay (two control adults and two control young trees and three pruned saplings), the final N for each diameter class was: pruned adult trees = 12; control adult trees = 10; pruned young trees = 20; control young trees = 18; pruned saplings = 15; and control saplings = 18.

Prior to pruning (July 2003), for all trees we recorded: basal diameter of all stems (using diameter tape or digital calliper), total tree height and lowest crown height (with digital hypsometer, resolution: 0.1 m) and largest and smallest crown diameters (with diameter tape, distance: 0.01 m). Equivalent basal diameter (EBD) was estimated for each tree using the formula:

$$EBD = 2\sqrt{(SBD_1/2)^2 + (SBD_2/2)^2 + \cdots + (SBD_n/2)^2}$$

where SBD_1, SBD_2 and SBD_n are the diameters at the base of the n tree stems (Alvarez et al., 2011a).

For each individual we estimated crown volume (V) following the formula proposed by Sharifi et al. (1982):

$V = 2/3\pi R_c^2 h$

with R_c being the average of largest and smallest crown radius and h the difference between total tree height and lowest crown height. In pruned trees, we left only one stem which was that with an erect shape and with the best health status (Patch and Felker, 1997b). Secondary branches on the remaining stem were eliminated from the base up to a height of 2 m in adults, up to 1.3 m in young trees and up to 0.9 m in saplings (Pasiecznik et al., 2001). Pruning was carried out using cutting tools (chainsaw or handsaw) at the time of dormancy (Elfadl and Luukkanen, 2003). Oblique cuts were made on the vertical axis of removed branches to prevent the likelihood of rot from water accumulation (Allen, 1986). The remaining individuals were left unpruned as controls. The above-described allometric measurements were replicated in pruned and control trees immediately after pruning and then on a yearly basis during the winters of 2004 through 2009.

Considering that *Prosopis* species easily produce shoots in areas near the cuts when apical dominance is broken (Meyer et al., 1971; Fisher, 1977), we counted the number of resprouts, measuring their diameter with calliper diameter (0.01 cm) and length with tape-measure (0.01 m). After each annual measurement, those resprouts (base of tree and main stem) produced in the previous growing season were cut off.

To compare each variable's response to pruning (%R) among diameter classes, we calculated the ratio (%) between pruned and control trees for each year, considering the average value of the variable in control trees as 100%. The slope of the curve for each diameter class represented the rate of the response of the variable in relation to control trees. We calculated:

$\%R = P_i \cdot C_i^{-1} \cdot 100$

where P_i represents the average value for the considered variable of the pruned trees in year "*i*" and C_i the average value of the control trees in year "*i*".

2.2.2. Trial II Effects of pruning intensity on young Prosopis trees

We selected 30 multi-stemmed trees of 3–7.5 cm diameter class. Before pruning (July 2004), we measured SBD of each stem, total tree height and largest and smallest crown diameter, and calculated EBD. During the winter of 2004, by using three treatments, 10 of the trees were pruned, leaving the main stem and lateral branches, thus removing approximately 50% of the crown (heavy pruning); from another 10 trees we removed the lateral branches, representing 25% of the crown (Intermediate pruning) (Elfadl and Luukkanen, 2003); and 10 *Prosopis* trees were left unpruned to serve as control. Pruning was made with a handsaw during dormancy (Elfadl and Luukkanen, 2003). The allometric measurements were replicated in pruned and control trees immediately after pruning and, subsequently, on a yearly basis during the winters of 2005 through 2009. We counted the number of resprouts on the stem, measuring their diameter and length. After each annual measurement, those resprouts (base of tree and main stem) produced in the previous growing season were cut off.

2.3. Data analysis

Although the use of repeated measures ANOVA for testing experimental trials in silviculture is widely known, this analysis does not contemplate the random effects provided by experimental units (Crawley, 2007; Baker et al., 2008). For this reason, we used linear mixed models (LMM) to analyze continuous variables such as total crown height, crown diameter and crown volume, EBD, resprout diameter, resprout length, and annual branch increase. For analyzing number of resprouts (discrete variable), we used generalized linear mixed models (GLMM).

Model selection was as follows: first, we selected models with the most informative random effect combination using likelihood ratio test (LRT). Then, we selected the best models from all possible fixed effects combinations using Akaike weights (Burnham and Anderson, 2002), which are based on the AIC scores for all models in the candidate set. Akaike weight is an absolute measure of support that sums to 1 across all candidate models, here we report results from all models with weights >0.005. Model selection was corroborated using "MuMIn", the multi-model inference package, which ranks the models according to AIC weights (Barton, 2013). When models for the same response variable differed in their δAIC < 4 (i.e., when there was low level of empirical support in considering candidate models), we estimated the mean parameters using weighted model-averaging (Burnham and Anderson, 2002), implemented in "MuMIn". Parameters were estimated by restricted maximum likelihood (REML) using the lme4 package (Bates et al., 2013) version 0.999999-2 in R 3.0.1 (R Development Core Team 2008).

For Trial I, the maximum model included three main fixed effects: pruning (P), diameter class (D) and year (Y), and their interactions. Similarly, in Trial II, the maximum model included two main fixed effects: intensity (I) and year (Y), and their interactions. In both experiments the factor "tree" identifying each of the individuals studied was considered a random effect, allowing the model to vary in both, intercept (trees) and slope (years) (Crawley, 2007; Bates et al., 2013).

3. Results

In both trials, pruned trees showed a fast response, increasing crown growth, while EBD growth was less evident and height growth was insignificant. Pruning also induced resprout development. These responses differed between both diameter classes and pruning intensities. In Appendixes A and B, the parameter estimates for each variable are shown for Trial I and Trial II, respectively.

3.1. Response to pruning by individuals of different diameter classes

3.1.1. Crown response

Crown variables showed, along with EBD, the most complex responses. The best-fitting model for crown volume was the maximum model, which included the three main explaining variables and all of their interactions (Table 1). Crown diameter, in turn, showed that the best model included the three main explaining variables and the Pruning–Year and Pruning–Diameter class interactions (Table 1). No growth was detected in the crown diameter or volume of adult and young control trees, and only a small growth was detected in control sapling trees. In contrast, the trend of pruned trees was positive, with an increment in crown diameter and volume in all three diameter classes, resulting in a decreasing difference between treatments over the years (Fig. 1a and b). The interaction between Pruning and Diameter class indicated that crown recovery was more pronounced in pruned saplings than in the other diameter classes (Fig. 2). Another variable related to crown of trees is annual branch length growth. This variable did not vary among diameter classes, since the best-fitting model included only the main effects Year and Pruning (Table 1). Branch growth was higher in pruned than in control trees and this difference was higher during the second and third year after pruning, being equal by the sixth year (Fig. 3a).

3.1.2. Stem diameter response

The best-fitting model for EBD included the three main explaining variables and the Pruning–Diameter class and Pruning–Year

Table 1
Model selection for variables measured in the evaluation of the pruning effect on different diametric classes trees, ranked using Akaike weights (wAIC). Effects tested in models: Y, year; D, diameter class; and P, pruning treatment, and their interactions. δAIC is the difference in AIC among candidate models. EBD, equivalent basal diameter.

Variable	Rank	Y	D	P	YxD	YxP	DxP	YxDxP	df	AICc	δAIC	wAIC
Crown diameter	1	x	x	x		x	x		12	676.4	0.00	0.664
	2	x	x	x		x			10	677.8	1.37	0.334
Crown volume		x	x	x	x	x	x	x	16	3454.7	–	0.997
EBD		x	x	x		x	x		16	2175.9	–	0.995
Total tree height	1		x						7	361.7	0.00	0.571
	2		x	x					8	362.5	0.85	0.373
	3		x	x			x		10	368.1	6.44	0.023
	4	x	x						8	368.6	6.94	0.018
	5	x	x	x					9	369.4	7.69	0.012
Annual branch length	1	x		x					7	−1230.3	0.00	0.991
	2	x		x		x			8	−1220.9	9.41	0.009
Resprout diameter	1	x		x		x			8	−373.3	0.00	0.790
	2			x					6	−370.5	2.80	0.194
	3	x		x					7	−365.0	8.28	0.013
Resprout length	1			x		x			6	−34.6	0.00	0.894
	2	x		x					8	−30.1	4.46	0.096
	3	x		x					7	−25.2	9.37	0.008
Resprout number	1	x		x		x			7	2619.0	0.00	0.4460
	2	x	x	x		x			9	2619.7	0.68	3180.1
	3	x	x	x		x	x		11	2621.4	2.46	310.06
	4	x	x	x	x	x			11	2622.7	3.73	90.031
	5	x	x	x	x	x	x		13	2624.3	5.36	

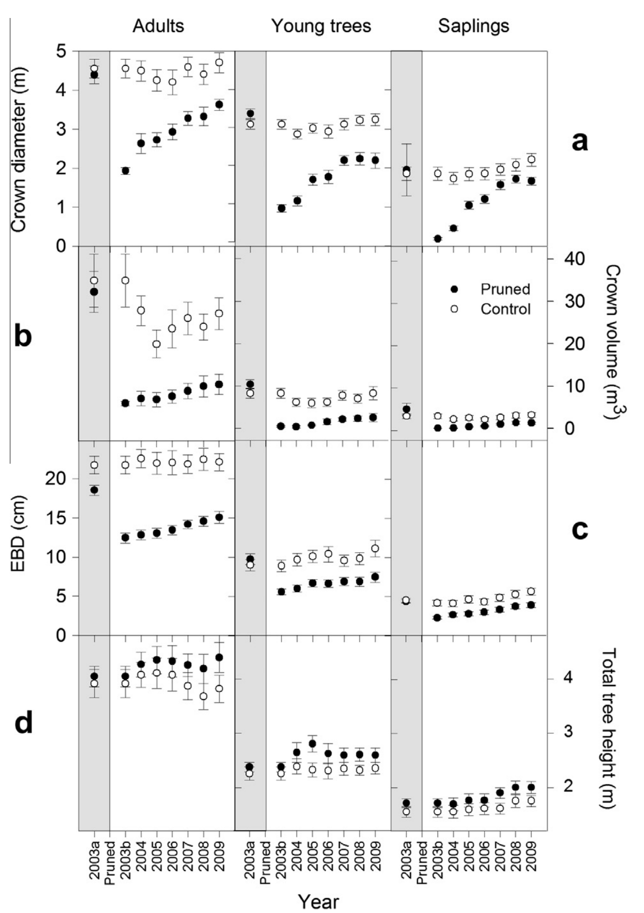

Fig. 1. Pruning effects on individuals of different diameter classes. Variables recorded before pruning and then annually measured: (a) crown diameter (m), (b) crown volume (m^3), (c) equivalent basal diameter (cm) and (d) total tree height (m). Dots represent the mean values and lines the standard error. The gray area represents the values of variables before pruning (2003a) and white area the annual mean after pruning.

interactions (Table 1). The significant Pruning–Diameter class interaction indicated that not all types of trees had the same response. In this case, adult trees showed a higher response to pruning than young trees and saplings (Figs. 1c and 2). The EBD response was evident in the different slope observed in adult trees, with the difference with the EBD of control trees declining in the last years of the trial. In young and sapling trees, the slope was similar between control and pruned trees, showing an EBD increment in control individuals that was not observed in adult trees (Fig. 1c).

3.1.3. Height response

Total tree height did not show a clear response to pruning. The best-fitting model included only the diameter class factor, showing the obvious differences in height among age classes (Table 1). The second model, with a δAIC < 4, also included the effect of pruning, making evident the slight increment in total height observed in pruned trees (Figs. 1d and 2).

3.1.4. Resprout response

Pruned individuals presented a higher number, diameter and length of resprouts than control individuals in all diameter classes (Fig. 3). For the number and diameter of resprouts, there was a significant Pruning–Year interaction (Table 1), showing a decrease in these variables in pruned trees along the trial duration (Table 1 and Fig. 3). In all three variables, the best models did not include interactions with “Diameter class”, indicating that a similar response was observed among diameter classes.

3.2. Effects of pruning intensity in young Prosopis trees

3.2.1. Crown response

Both crown diameter and volume included pruning intensity in the best models, but only crown volume included the interaction with year (Table 2). Crown volume growth increased as pruning intensity increased (Fig. 4b). As a consequence, the slope of both pruning intensities was higher than that of controls, and there were no differences among pruning intensities after four years since trial began (Fig. 4b). Crown diameter was similar during the last year of the trial, but the Year–Pruning intensity interaction was not significant (Fig. 4a).

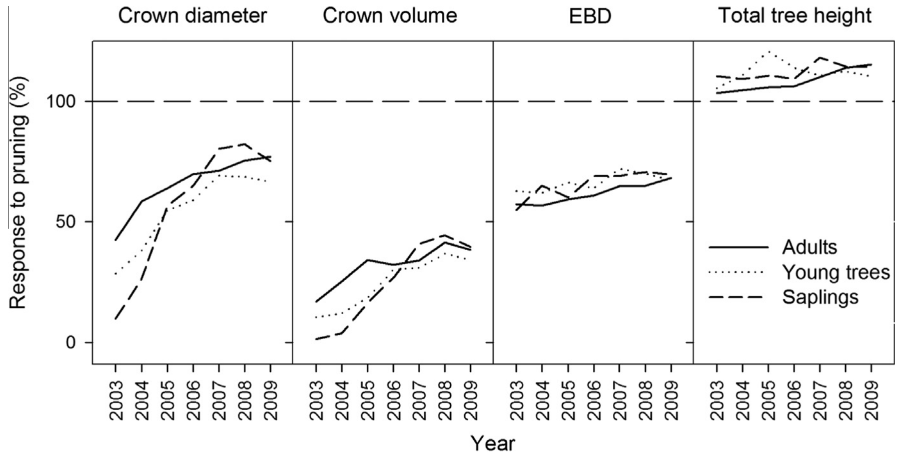

Fig. 2. Response to pruning of the selected variables for different diameter classes: crown diameter, crown volume, EBD and total tree height. The response to pruning was expressed as percentages representing the relation between mean values of the pruned treatment and control trees for each year. Long-dashed line represents the mean value of the control trees (100%), for each diameter class.

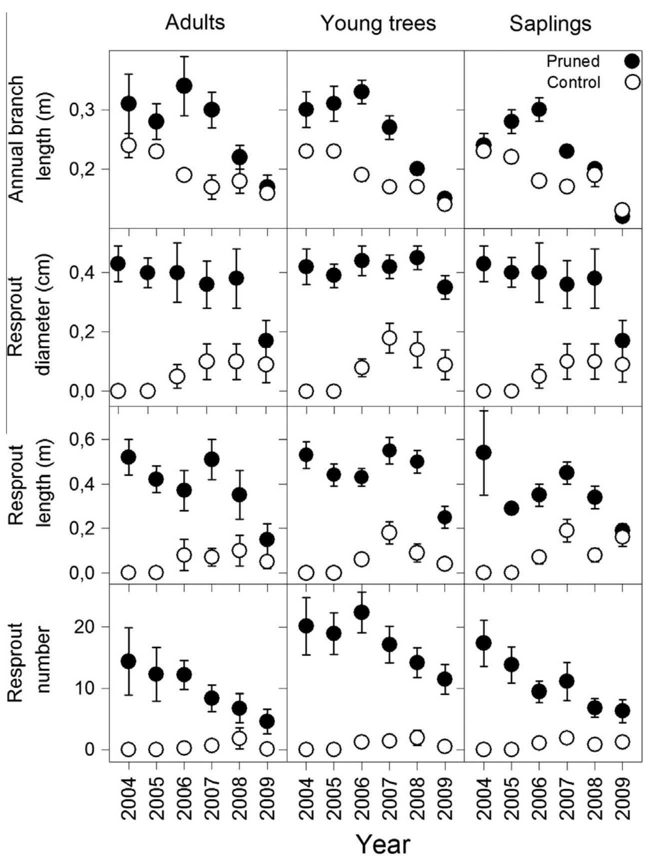

Fig. 3. Pruning effects on individuals of different diameter classes on annual branch growth and resprout generation. (a) Annual branch length growth (m), (b) resprout diameter (cm), (c) resprout length (m), and (d) resprout number. Dots represent the mean value and lines the standard error.

Only the effect of Year was included in the best-fitting model for the Annual branch length growth, indicating no clear response of this variable to pruning intensity (Table 2 and Fig. 4e).

3.2.2. Stem diameter response

The best-fitting model for EBD included the two main factors but not their interaction, indicating that all three treatments showed a proportional increase in EBD across years (Fig. 4c).

3.2.3. Height response

None of the factors tested was important to explain the response of Total tree height, the null model was better than models that included explaining factors (Table 2), indicating no response of this variable to treatments (Fig. 4d).

3.2.4. Resprout responses

The number, diameter and length of resprouts increased as pruning intensity increased (Fig. 4). The best-fitting models for the three variables included Pruning intensity as explaining variables, and only resprout number included the Year–Pruning intensity interaction (Table 2), indicating a decrease in the number of resprouts of pruned individuals over the five years of measurements (Fig. 4f).

4. Discussion

The first response found for the different diameter classes of pruned *Prosopis* trees and the different pruning intensities applied was an increase in crown recovery and branch growth. In contrast, there was no initial response in the growth of EBD, since the increase in EBD was evident only in the last years of the trials. This suggests that initially the reduction of photosynthetic area is more important than the benefits obtained from reduced stem competition, which is not consistent with our first hypothesis. This first response implies assimilate partitioning that tends to recovery of the leaf area, which could be due to an improved water status of the plant from leaf area reduction, or to a compensatory growth with the consequent increase in photosynthetic rate (Elfadl and Luukkanen, 2003). Only when photosynthetic area is recovered does the reduction of competition among stems appear to be effective in increasing diameter growth of the remaining area.

The first scientific silvicultural studies relative to pruning (in live crown of young Douglas-Fir) would suggest that this treatment increased the diameter of the remaining stem when the percentage of crown removal did not exceed 25% (Stein, 1955). Notwithstanding, recent studies suggest that with higher pruning intensities, diameter growth does not increase (Chandrashekara, 2007; Pinkard et al., 2004), or even decreases in the cases where over 75% of the crown is removed (Chandrashekara, 2007). However, the recovery of photosynthetic capacity observed for all pruning intensities in our work would allow thinking of a later increase in EBD as is observed after five years, albeit further monitoring will be required to test the final effect on diameter growth. In *P. glandulosa*, an increase in EBD was recorded after three years

Table 2
Model selection for variables measured to evaluate the effects of different pruning intensities, ranked using Akaike weights (wAIC). Effects tested in models: Y, year; I, pruning intensity; and their interaction. δAIC is the difference in AIC among candidate models. EBD, equivalent basal diameter.

Variable	Rank	Y	I	YxI	df	AICc	δAIC	wAIC
Crown diameter	1		x		7	204.4	0.00	0.873
	2	x	x		8	208.8	4.41	0.096
	3				5	211.7	7.31	0.023
Crown volume	1	x	x	x	10	1010.0	0.00	0.584
	2	x	x		8	1010.6	0.66	0.394
	3		x		7	1014.6	4.57	0.056
EBD	1	x	x		8	567.0	0.00	0.882
	2	x	x	x	10	571.1	4.12	0.112
	3		x		7	577.1	10.1	0.006
Total tree height	1				5	168.5	0.00	0.872
	2	x			6	173.7	5.15	0.066
	3		x		7	174.0	5.43	0.058
Annual branch length	1	x			6	−290.1	0.00	0.969
	2				5	−283.0	7.09	0.028
Resprout diameter	1		x		7	21.8	0.00	0.943
	2	x	x		8	27.4	5.61	0.057
Resprout length	1		x		7	34.2	0.00	0.935
	2	x	x		8	39.5	5.34	0.065
Resprout number	1	x	x	x	9	536.7	0.00	0.518
	2		x		6	536.9	0.18	0.474
	3	x	x		7	545.2	8.45	0.008

from pruning, coupled with clearing and ploughing of plots and removal of herbaceous biomass from beneath *P. glandulosa* individuals (Cornejo-Oviedo et al., 1991). Responses of adult and young *Prosopis* trees to pruning did partially match the proposed hypothesis (higher response in adult vs. young *Prosopis* trees). A higher response in adult plants was evident in EBD only after five years from pruning. However, crown response was higher in younger plants. This could be related to reduced competition among crowns of different stems in adult plants, and to the consequent increment in the remaining stem. By contrast, in young trees, where there is no high crown competition among stems, we observed no stem diameter response, but noted a fast response in crown growth, indicating that stem growth is still limited by photosynthetic area.

Regarding pruning intensity, our results were not consistent with the hypothesis that individuals with intermediate pruning elicit a major response in crown and stem growth variables than those heavily pruned, basically because of lower crown volume loss. In contrast, we found that crown diameter and volume responses increase as increased pruning intensity. These data are consistent with observations by Elfadl and Luukkanen (2003) for *P. juliflora*, where leaf biomass growth increases significantly with increasing pruning intensity, which is related to higher moisture content in leaves and wood, higher efficiency in water use, or the action of photosynthetic compensatory effects (Heinchel and Turner, 1983; Helms, 1964, 1965; Roth et al., 2007).

Depending on management objectives, pruning has been suggested as an essential tool for increasing wood productivity (Nicholas and Brown 2002), and for improving the quality of forest products (knot–clear wood), or fruit production (Meyer and Felker, 1990; Diaz Celis, 1995; Patch and Felker, 1997b). The fast crown recovery and slow EBD growth response suggest that, in a first stage, pruning could contribute to the goal of improving the shape of the tree, though not to wood production (Beadle et al., 2007). In addition, branch removal would contribute 21.3–54.3 kg of firewood in adults (equivalent to 2–3 stems), 6–12 kg in young trees, and less than 3 kg in saplings (Alvarez et al., unpublished).

One of the problems of using pruning as management tool is the generation of resprouts from intervened plants (Patch et al., 1998). In our work, we found presence of resprouts in all pruning treatments, although their number and length decreased in all diameter classes assessed over the 6 years recorded. In addition, resprout generation increased with pruning intensity. This differential effect produced on trees by pruning intensity can be a useful tool in planning silvicultural management. Resprout generation is explained by the generation of immediate signals that stimulate activation of new growing points on the remaining stem (Coder, 1998). In our study, resprout control was done through annual cutting, as performed in Sudan by Elfadl (1997), resulting in reduced resprouting at the end of the trial. Application of herbicides, plastic mesh, and oil-derived compounds has been tested to inhibit resprout appearance from the base of the stem of pruned *Prosopis* trees in diverse parts of the world (Ueckert et al., 1979; Cornejo-Oviedo et al., 1991; Patch and Felker, 1997a; Tewari et al., 2000). The use of these types of treatments in the northeast of Mendoza would depend on economic assessment and acceptance by woodland inhabitants. Including the number of stems as a variable of forestry use is a recently developed practice (Beadle et al., 2007; Hein et al., 2007). Previous studies on wood growth in *P. flexuosa* indicate that an eventual management of adult multi-stemmed *Prosopis* trees should combine use of the dead wood present in the trees with removal of lateral branches (between 20 and 27 cm in EBD) at an age of around 80 years, as a tool to avoid competition among stems (Alvarez et al., 2011a, 2011b; Vázquez et al., 2011). The results obtained in the present study reinforce this idea, suggesting the possibility of including multi-stemmed trees in a model of use that considers applying pruning to improve tree shape and increase production of firewood or poles. Thus, pruning practices would promote the conversion of firewood-producing woodlands to pole-producing woodlands (Allen, 1986; SAGPyA, 2003), while the product of extraction can be part of the domestic use of the local people (firewood and poles).

We concluded that pruning induces fast recovery of photosynthetic area but not an initial increase in diameter growth, suggesting a control of growth imposed by photosynthetic area. The crown response to pruning is more marked in young and sapling individuals and at the highest pruning intensity. Therefore, pruning is suggested as a tool to improve the shape of *Prosopis* in the short run, and increase stem diameter growth in the long run. This practice could be potentially used to obtain poles and firewood without a decrease in wood productivity but with an increase in branch

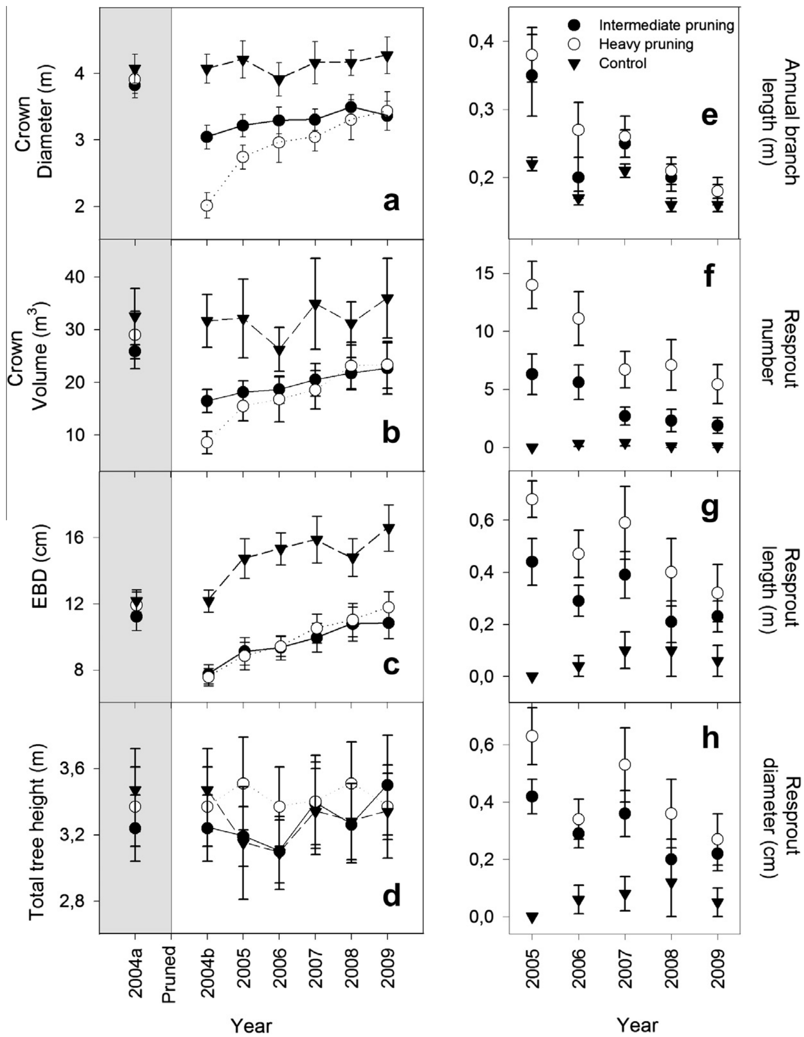

Fig. 4. Effects of different pruning intensities on the growth of young trees. On the left: variables recorded before pruning (grey area: 2004) and then annually measured: crown diameter (m), crown volume (m^3), EBD (cm) and total tree height (m). On the right: variables recorded after the first year of pruning and annual measures: Annual branch length growth (m), resprout length (m), resprout number and resprout diameter (cm). Dots represent the mean area and lines the standard error.

growth. In consequence, pruning could be included in forest management of woodlands dominated by multi-stemmed trees, and in models of sustainable management at local scale.

Acknowledgements

We thank Gualberto Zalazar, Anahí Miner, Erica Cesca, Hugo Debandi, Alejandra Giantomasi, Ana Srur, and Carolina Szimañski for help in the field, and Nelly Horak for assisting with the English language. Funding was provided by CONICET (Argentina) and Universidad Nacional de Cuyo (06-A452 and 06-PA03).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2013.09.033.

References

Allen, K., 1986. Poda de árboles ornamentales. Consejo Superior de Investigaciones Científicas, Madrid.

Alvarez, J.A., Villagra, P.E., 2009. *Prosopis flexuosa* DC. (Fabaceae, Mimosoideae). Kurtziana 35, 49–63.

Alvarez, J.A., Villagra, P.E., Cony, M.A., Cesca, E., Boninsegna, J.A., 2006. Estructura y estado de conservación de los bosques de *Prosopis flexuosa* D.C. en el Noreste de Mendoza, Argentina. Revista Chilena de Historia Natural 79, 75–87.

Alvarez, J.A., Villagra, P.E., Villalba, R., 2011a. Factors controlling deadwood availability and branch decay in two *Prosopis* woodlands in the Central Monte, Argentina. Forest Ecology and Management 262, 637–645.

Alvarez, J.A., Villagra, P.E., Villalba, R., Cony, M.A., Alberto, M., 2011b. Wood productivity of *Prosopis flexuosa* D.C. woodlands in the central Monte: influence of the population structure and tree growth habit. Journal of Arid Environments 75, 7–13.

Aranibar, J.N., Villagra, P.E., Gomez, M.L., Jobbágy, E., Quiroga, M., Wuilloud, R.G., Monasterio, R.P., Guevara, A., 2011. Nitrate dynamics in the soil and unconfined aquifer in arid groundwater coupled ecosystems of the Monte desert, Argentina. Journal of Geophysical Research, 1–12.

Baker, P.J., Robinson, A.P., Ewel, J.J., 2008. Sudden and sustained response of *Acacia koa* crop trees to crown release in stagnant stands. Canadian Journal Forest Research 38, 656–666.

Barton, K., 2013. MuMIn: Multi-model inference [R package]. <http://cran.r-project.org/>.

Bates, D., Maechler, M., Bolker, B., 2013. lme4: Linear mixed-effects models using S4 classes [R package]. <http://cran.r-project.org/>.

Bayala, J., Teklehaimanot, Z., Ouedraogo, S., 2004. Fine root distribution of pruned trees and associated crops in a parkland system in Burkina Faso. Agroforestry Systems 60, 13–26.

Beadle, C., Barry, K., Hardiyanto, E., Irianto, R., Junarto, Mohammed, C., Rimbawanto, A., 2007. Effect of pruning *Acacia mangium* on growth, form and heart rot. Forest Ecology and Management 238, 261–267.

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference: a practical information-theoretic approach. In: Effects of Pruning on Radial Growth and Biomass Increment of Trees Growing in Homegardens of Kerala, second ed. New York, Springer-Verlag, Chandrashekara, U.M., 2007.. India Agroforestry Systems 69, 231–237.

Chandrashekara, U.M., 2007. Effects of pruning on radial growth and biomass increment of trees growing in homegardens of Kerala, India. Agroforestry Systems 69, 231–237.

Coder, K.D., 1998. Pruning Effects on Tree Growth: Growth Regulation Consequences. FOR98-5. University of Georgia Cooperative Extension Service Forest Resources publication. pp. 1–3.

Cony, M., 1995. Reforestación racional de zonas áridas y semiáridas con árboles multipropósitos. Interciencia 20, 249–253.

Cony, M.A., Villagra, P.E., Alvarez, J.A., 2004. Producción actual y potencial de leña y madera en algarrobales del Monte. Argentina. Pautas de manejo y aprovechamiento sustentables. Segunda Reunión Binacional de Ecología. Mendoza.

Cornejo-Oviedo, E.H., Meyer, J.M., Felker, P., 1991. Thinning dense sapling stands of mesquite (*Prosopis glandulosa* var. *glandulosa*) to optimize timber productions and pasture improvement. Forest Ecology and Management 46, 189–200.

Crawley, M.J., 2007. 19 Mixed-effects models. In: Ltd, J.W.S. (Ed.) The R Book. The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England. pp. 627–660.

D'Antoni, H.L.D., Solbrig, O.T., 1977. Algarrobos in South American cultures: past and present. In: Simpson, B.B. (Ed.) Mesquite. Its biology in two Desert Scrub Ecosystems. US/IBP Synthesis Series 4. Dowden, Hutchinson & Ross Inc.. pp. 1–26.

Diaz Celis, A., 1995. Los algarrobos. CONCYTEC, Lima.

Elfadl, M.A., 1997. Management of Prosopis juliflora for use in agroforestry systems in the Sudan. University of Helsinki, Helsinki.

Elfadl, M.A., Luukkanen, O., 2003. Effect of pruning on *Prosopis juliflora*: considerations for tropical dryland agroforestry. Journal of Arid Environments 53, 441–455.

Estrella, H.A., Heras, V.A., Guzzeta, V.A., 1979. Registro de elementos climáticos en áreas críticas de la provincia de Mendoza. Cuaderno Técnico (IADIZA-Mendoza) vol. 1, pp. 49–71.

F.A.O., 1994. Consulta de expertos sobre el avance de la agroforesteria en zonas aridas y semiaridas de america latina y el caribe.

Fagg, C.W., Stewart, J.L., 1994. The value of *Acacia* and *Prosopis* in arid and semi-arid environments. Journal of Arid Environment 27, 3–25.

Felker, P., Guevara, J.C., 2003. Potential of commercial hardwood forestry plantations in arid lands – an economic analyses of *Prosopis* lumber production in Argentina and the United States. Forest Ecology and Management 186, 271–286.

Fisher, C.E., 1977. Mesquite and modern man in Southwestern North America. In: Simpson, B.B. (Ed.), Mesquite, Its biology in two desert ecosystems, Stroudsburg, Pennsylvania, pp. 177–188.

González Loyarte, M.M., Martínez Carretero, E., Roig, F.A., 1990. Forest of Prosopis flexuosa var. flexuosa (Leguminosae in the NE of Mendoza. I. Structure and dynamism in the area of the ''Telteca Natural Reserve''. Documents Phytosociologiques n.s. vol. XII, pp. 285–289.

Hein, S., Makinen, H., Yue, C., Kohnle, U., 2007. Modelling branch characteristics of Norway spruce from wide spacings in Germany. Forest Ecology and Management 242, 155–164.

Heinchel, G.H., Turner, N.C., 1983. CO_2 assimilation of primary and regrowth foliage of red maple (*Acer rubrum* L.) and red oak (*Quercus rubra* L.): response to defoliation. Oecologia 57, 14–19.

Helms, J.A., 1964. Apparent photosynthesis of Douglas-fir in relation to silvicultural treatment. Forest Science 10, 432–442.

Helms, J.A., 1965. Diurnal and seasonal patterns of net assimilation in Douglas-Fir, *Pseudotsuga Menziesii* (Mirb). Franco, as influenced by environment. Ecology 46, 698–708.

Meyer, J., Felker, P., 1990. Pruning mesquite (*Prosopis glandulosa* var. *glandulosa*) saplings for lumber production and ornamental use. Forest Ecology and Management 36, 301–306.

Meyer, R.E., Morton, H.L., Haas, R.H., Robison, E.D., Riley, T.E., 1971. Morphology and anatomy of honey mesquite. USDA Tech. Bull. 1423, 186.

Mooney, H.A., Simpson, B.B., Solbrig, O.T., 1977. Phenology, morphology, physiology. In: Simpson, B.B. (Ed.) Mesquite. Its biology in two Desert Scrub Ecosystems. U.S./ibp synthesis series 4. Dowden, Hutchinson & Ross Inc.. pp. 26–43.

Nicholas, I., Brown, I., 2002. Blackwood. A handbook for growers and users. Forest Research Bulletin 225, 100.

Pasiecznik, N.M., Felker, P., Harris, P.J.C., Harsh, L.N., Cruz, G., Tewari, J.C., Cadoret, K., Maldonado, L.J., 2001. The *Prosopis juliflora – Prosopis pallida* complex: a monograph, HDRA, Coventry.

Patch, N.L., Felker, P., 1997a. Silvicultural treatments for sapling mesquite (*Prosopis glandulosa* var. *glandulosa*) to optimize timber production and minimize seedling encroachment. Forest Ecology and Management 96, 231–240.

Patch, N.L., Felker, P., 1997b. Influence of silvicultural treatments on growth of mature mesquite (*Prosopis glandulosa* var. *glandulosa*) nine years after initiation. Forest Ecology and Management 94, 37–46.

Patch, N.L., Geesing, D., Felker, P., 1998. Suppression of resprouting in pruned mesquite (*Prosopis glandulosa* var *glandulosa*) saplings with chemical or physical barrier treatments. Forest Ecology and Management 112, 23–29.

Peter, I., Lehmann, J., 2000. Pruning effects on root distribution and nutrient dynamics in an acacia hedgerow planting in northern Kenya. Agroforestry Systems 50, 59–75.

Pinkard, E.A., Mohammed, C., Beadle, C.L., Hall, M.F., Worledge, D., Mollon, A., 2004. Growth responses, physiology and decay associated with pruning plantation-grown *Eucalyptus globulus* Labill. and *E. nitens* (Deane and Maiden) Maiden. Forest Ecology and Management 200, 263–277.

R Development Core Team, 2008. R: A Language and Environment for Statistical Computing [Computer Program]. R Foundation for Statistical Computing, Vienna Austria.

Roig, F.A., 1993. Aportes a la etnobotánica del género Prosopis. In: IADIZA (Ed.) Contribuciones Mendocinas a la Quinta Reunión de Regional para América Latina y el Caribe de la Red de Forestación del CIID. Conservación y Mejoramiento de Especies del Género Prosopis., Mendoza, Argentina. pp. 99–119.

Roth, G.A., Whitford, W.G., Steinberger, Y., 2007. Jackrabbit (*Lepus californicus*) herbivory changes dominance in desertified Chihuahuan Desert ecosystems. Journal of Arid Environments 70, 418–426.

Rundel, P., Villagra, P.E., Dillon, M.O., Roig-Juñent, S.A., Debandi, G., 2007. Arid and semi-arid ecosystems. In: Veblen, T.T., Young, K., Orme, A. (Eds.), The physical geography of South America. Oxford University Press. pp. 158–183.

SAGPyA., 2003. Investigación forestal al servicio de la producción. Resultados aplicables al cultivo de bosques y la producción de madera en Argentina, 1997–2000. Primera entrega. pp. 127.

Sharifi, M.R., Nilsen, E.T., Rundel, P.W., 1982. Biomass and net primary production of *Prosopis glandulosa* (Fabaceae) in the Sonoran Desert of California. American Journal of Botany 69, 760–767.

Stein, W.I., 1955. Pruning to different heigths in young Douglas-Fir. Journal of Forestry 53, 352–355.

Tewari, J.C., Harsh, L.N., 1998. Forestry research in arid tract of India. In: Faroda, A.S., Singh, M. (Eds.), Fifty Years of Arid Zone, Research in India. CAZRI, Jodhpur, India, pp. 307–322.

Tewari, J.C., Harris, P.J.C., Harsh, L.N., Cadoret, K., Pasiecknik, N.M., 2000. Managing Prosopis juliflora (Vilayati babul): A Technical Manual. CAZRI, Jodhpur, India and HDRA, Coventry, UK. pp. 96.

Ueckert, D., Smith, L., Allen, L., 1979. Emergence and survival of honey mesquite seedlings on several soils in west Texas. Journal of Range Management 32, 284–287.

Vázquez, D.P., Alvarez, J.A., Debandi, G., Aranibar, J., Villagra, P.E., 2011. Ecological effects of removal of coarse woody debris in a dry, warm woodland ecosystem. Basic and Applied Ecology 12, 722–732.

Villagra, P.E., Boninsegna, J.A., Alvarez, J.A., Cony, M., Cesca, E., Villalba, R., 2005. Dendroecology of *Prosopis flexuosa* woodlands in the Monte desert: implications for their management. Dendrochronologia 22, 209–213.